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In Situ Modification and Manipulation of  
Stem Cells of the Central Nervous System

Cross-References to Related Applications

This is a continuation-in-part application of patent application U.S.S.N. 07/726,812,  
5 filed July 8, 1991. This application is also related to U.S.S.N. 07/961,813, filed  
October, 16, 1992, U.S.S.N. 07/967,622, filed October 28, 1992, and U.S.S.N.  
08/010,829, filed January 29, 1993; all of which are hereby incorporated by  
reference.

Field of the Invention

10 The present invention is directed to the *in situ* (*in vivo*) modification and manipulation,  
via genetic or epigenetic means, of endogenous precursor cells in the mammalian  
central nervous system (CNS). More particularly, the invention is related to a method  
of directly manipulating the endogenous precursor cells *in situ* (*in vivo*) for the  
purpose of using them as vehicles for the delivery of agents to the CNS or to induce  
15 them to divide, differentiate and migrate so as to replace dysfunctional cells or those  
lost to injury or disease.

Background of the Invention

Development of the mammalian nervous system begins in the early stage of fetal  
development and continues until the early post-natal period. The mammalian central  
20 nervous system (CNS) is composed of three cell types: neurons, astrocytes and  
oligodendrocytes. While neurons are generated primarily during the fetal period,

oligodendrocytes and astrocytes are generated during the early post-natal period. By the late post-natal period the CNS has its full complement of nerve cells.

Unlike many other cells found in different tissues, the differentiated cells of the adult mammalian CNS have little or no ability to enter the mitotic cycle and generate new nerve cells. While it is believed that there is a limited and slow turnover of astrocytes (Korr et al., J. Comp. Neurol., 150:169, 1971) and that progenitors for oligodendrocytes (Wolsqijk and Noble, Development, 105:386, 1989) are present, the generation of new neurons does not occur. While a few mammalian species (e.g. rats) exhibit the limited ability to generate new neurons in restricted adult brain regions such as the dentate gyrus and olfactory bulb (Kaplan, J. Comp. Neurol., 195:323, 1981; Bayer, N.Y. Acad. Sci., 457:163, 1985) this does not apply to all mammals; and the generation of new CNS cells in adult primates does not occur (Rakic, Science, 227:1054, 1985). This inability to produce new nerve cells in most mammals (and especially primates) may be advantageous for long-term memory retention; however, it is a distinct disadvantage when the need to replace lost neuronal cells arises due to injury or disease.

CNS disorders encompass numerous afflictions such as neurodegenerative diseases (e.g. Alzheimer's and Parkinson's), acute brain injury (e.g. stroke, head injury, cerebral palsy) and a large number of CNS dysfunctions (e.g. depression, epilepsy, and schizophrenia). In recent years neurodegenerative disease has become an important concern due to the expanding elderly population which is at greatest risk for these disorders. These diseases, which include Alzheimer's Disease, Multiple Sclerosis, Huntington's Disease, Amyotrophic Lateral Sclerosis, and Parkinson's Disease, have been linked to the degeneration of neural cells in particular locations of the CNS, leading to the inability of these cells or the brain region to carry out their intended function. In addition to neurodegenerative diseases, acute brain injuries often result in the loss of neural cells, the inappropriate functioning of the affected brain region, and subsequent behavior abnormalities. Probably the largest area of CNS dysfunction (with respect to the number of affected people) is not characterized by a loss of neural cells but rather by an abnormal functioning of existing neural cells. This may be due to inappropriate firing of neurons, or the abnormal synthesis, release,

and processing of neurotransmitters. Some of these dysfunctions are well studied and characterized disorders such as depression and epilepsy, others are less understood disorders such as neurosis and psychosis.

To date, treatment for CNS disorders has been primarily via the administration of pharmaceutical compounds. Unfortunately, this type of treatment has been fraught with many complications including the limited ability to transport drugs across the blood-brain barrier and the drug-tolerance which is acquired by patients to whom these drugs are administered long-term. For instance, partial restoration of dopaminergic activity in Parkinson's patients has been achieved with levodopa, which is a dopamine precursor able to cross the blood-brain barrier. However, patients become tolerant to the effects of levodopa, and therefore, steadily increasing dosages are needed to maintain its effects. In addition, there are a number of side effects associated with levodopa such as increased and uncontrollable movement.

Recently, the concept of neurological tissue grafting has been applied to the treatment of neurodegenerative diseases such as Parkinson's Disease.

An emerging technology for treating neurological disorders entails the transplantation of cells into the CNS to replace or compensate for loss or abnormal functioning of the host's nerve cells. While embryonic CNS cells have given the best results in human trials (Winder et al., New Eng. J. Med., 327:1556, 1992) and are the preferred donor tissue, due to ethical and political considerations which limit the use of these cells, other types of donor tissue are being developed. These include: genetically modified neural cell lines (Renfranz et al., Cell, 66:173, 1991; Synder et al., Cell, 68:1, 1992), fibroblasts (Kawaja et al., J. Neurosci., 12:2849, 1992), muscle cells (Jiao et al., Nature, 363:456, 1993), glial progenitor cells (Groves et al., Nature, 362:453, 1993) and encapsulated cells (Hoffman et al., Exp. Neurol., 132:100, 1993).

While transplantation approaches represent a significant improvement over currently available treatments for neurological disorders, they suffer from a number of significant drawbacks. For example, upon transplantation, some cell types fail to integrate with host tissue. Another disadvantage is that immunological incompatibility

between donor and host could result in the rejection of the implanted cells. There is also the potential that the transplanted cells can result in tumor formation or pass infectious agents from the donor tissue to the host. Another significant drawback of transplantation procedures is that due to the invasiveness of the procedures, which  
5 carry the risks involved in any major neurosurgical operation, damage to healthy brain tissue could occur.

Leblond (NCI Monograph, 14:19, 1963) has classified adult mammalian tissue into three categories based on the rate of cell turnover within the population. These are:

1. Static populations, like the nervous system, where there is little or no division  
10 and cells formed during development persist for the animal's lifetime;
2. Tissues having a conditionally renewing population of cells, such as the liver, where there is little cell division under normal conditions but where new cells can generate in response to an appropriate stimulus;
3. Continually renewing populations, such as the blood and squamous epithelium,  
15 where differentiated cells have a short life span and are continually being replaced by a subpopulation of cells referred to as stem cells.

The critical identifying feature of a stem cell is its ability to exhibit self-renewal or to generate more of itself. The simplest definition of a stem cell would be a cell with the capacity for self-maintenance. A more stringent (but still simplistic) definition of  
20 a stem cell is provided by Potten and Loeffler (Development, 110:1001, 1990) who have defined stem cells as "undifferentiated cells capable of a) proliferation, b) self-maintenance, c) the production of a large number of differentiated functional progeny, d) regenerating the tissue after injury, and e) a flexibility in the use of these options."

The role of stem cells is to replace cells that are lost by natural cell death, injury or  
25 disease. The presence of stem cells in a particular type of tissue usually correlates with tissues that have a high turnover of cells. However, this correlation may not

always hold as stem cells are thought to be present in tissues (i.e., liver [Travis, Science, 259:1829, 1993]) that do not have a high turnover of cells.

The low turnover of cells in the mammalian CNS together with the inability of the adult mammalian CNS to generate new cells in response to the loss of cells following injury or disease has lead to the assumption that the adult mammalian CNS does not contain stem cells. However, cells exhibiting stem cell characteristics *in vitro* have recently been isolated from the CNS. This cell is present in the embryo (Reynolds et al., J. Neurosci., 12:4565, 1992) through to the adult (Reynolds and Weiss, Science, 255:1707, 1992), suggesting that adult CNS, although it does not generate new cells in response to injury or disease, has the capacity to generate new cells and to repair itself via proliferation and differentiation of stem cells and their progeny in a manner analogous to the hematopoietic system.

In consideration of the limitation and deficiencies attendant in the prior art with respect to therapies for treating CNS disorders, it is apparent that there exists a need in the art for a method of treating CNS disorders which involves replacing cells lost to injury or disease, but that does not involve invasive transplantation procedures and the disadvantages attendant with such procedures. In addition, due to the problems associated with pharmaceutical compounds, there exists a need in the art for a method of treating CNS disorders which involves the direct delivery of compounds to the CNS by other CNS cells thereby circumventing the use of infusion pumps and the blood-brain barrier.

#### Summary of the Invention

It is an object of this invention to provide a method for the replacement of cells lost to injury, disease or dysfunction by inducing endogenous precursor cells to proliferate/differentiate and/or migrate within the CNS.

It is a further object of this invention to provide a method for the delivery of agents to the CNS by the genetic or epigenetic manipulation of endogenous precursor cells.

It is an object of this invention to provide a method for increasing the *in vitro* yield of stem cells by epigenetic manipulation of endogenous precursor cells.

These objects are accomplished by the methods disclosed below. Additional objects and features of the invention will be apparent to those skilled in the art from the following detailed description and appended claims when taken in conjunction with the figures.

A method for the *in situ* proliferation of neural precursor cells is described wherein one or more growth factors is administered to a ventricle of the central nervous system to induce the proliferation of the precursor cells.

10 A method for the *in situ* genetic modification of neural precursor cells is also described wherein genetic material is administered to a CNS ventricle to infect the precursor cells. The genetic material encodes a neurological agent selected from the group consisting of growth factors, growth factor receptors, neurotransmitters, neurotransmitter receptors, neuropeptides, growth factor synthesizing enzymes, and  
15 neurotransmitter synthesizing enzymes.

Also disclosed is a method of *in vitro* proliferation of precursor cells comprising the steps of administering one or more growth factors to a CNS ventricle of a living mammal, removing tissue lining the CNS ventricle, dissociating the tissue to separate precursor cells, and exposing the precursor cells to a culture medium containing at a  
20 growth factor that induces proliferation of the cells.

A method of treating a mammal suffering from a neurological disorder caused by lost or damaged neural cells is also described wherein one or more growth factors is administered to a CNS ventricle of the mammal to induce the *in situ* proliferation, migration, and differentiation of precursor cells lining the ventricle so as to replace  
25 the lost or damaged neural cells.

### Brief Description of the Figures

**Figures 1a-1c** show differentiated cells that were generated from stem cells isolated from the adult conus medullaris. Tissue containing the conus medullaris was dissected from adult mice. The stem cells were isolated and cultured in the presence of 20  
5 ng/ml of EGF and bFGF together. They generated neurons, astrocytes, and oligodendrocytes as indicated by triple label indirect immunocytochemistry with antisera to MAP-2 (Fig. 1A), GFAP (Fig. 1B) and O4 (Fig. 1C) respectively.

**Figure 2** shows the number of cells proliferating in the subependyma after various thymidine kill treatments. Control mice received no tritiated-thymidine (3H-  
10 thymidine) and were considered to have 100% of a proliferating subependymal cell population. Animals that received a series of injections on day 0 in order to kill the constitutively proliferating population of cells had 85% of control values on day 8. Animals that received a series of 3H-thymidine injections on day 0 and on day 2 had 45% of control values 8 days after the last injection (day 10). Animals that received  
15 a series of 3H-thymidine injections on day 0 and day 4 had 85% of control values on day 12. This suggests that stem cells are recruited into the proliferative mode two days after the initial kill and that most have become quiescent again by day 4.

**Figure 3** shows the number of neurosphere formed *in vitro* from animals subjected to various 3H-thymidine treatments *in vivo*. Animals received the same series of  
20 injections as illustrated in Figure 2. Control animals received saline injections. Mice were sacrificed 16-20 hours following the last 3H-thymidine injection and the brains were removed and cultured in order to assess the number of neurospheres that formed following each thymidine kill treatment. Animals that received 3H-thymidine on day 0 (which kills the normally proliferating subependymal cells) formed the same number  
25 of spheres as control animals, suggesting that the constitutively proliferating subependymal cells are not the source of stem cells isolated *in vitro*. Animals that received a second series of injections on day 2 formed 45% the number of neurospheres relative to control values. Animals that received a second series of injections on day 4 formed nearly as many neurospheres as the control animals,  
30 suggesting that the neurosphere-forming multipotent stem cell, which is isolated *in*

*vitro* in the presence of growth factors such as epidermal growth factor, comes from the relatively quiescent stem cell population within the subependyma *in vivo*.

**Figures 4a and 4b** demonstrate the proliferation and migration of retrovirally-labelled precursor cells in the subependyma in response to EGF-infusion *in vivo* into the lateral ventricle. The animals of Figure 4a and 4b had replication incompetent retroviruses containing the  $\beta$ -galactosidase gene injected into the lateral ventricles of their forebrains. Additionally, the animal of Figure 4b had an osmotic mini-pump filled with 33  $\mu\text{g/ml}$  EGF implanted at the same site as the injection. Six days later the brains of both animals were fixed and processed for  $\beta$ -gal histochemistry. With the control animal (Fig. 4a) retrovirally labelled cells (open arrow) resided closely to the lateral ventricle wall. The animal that received EGF infusion had many more labelled cells. Additionally the proliferated cells of the EGF-infused animal had migrated away from the lateral ventricle wall (bar represents 200  $\mu\text{m}$ ).

**Figure 5** demonstrates that EGF infusion *in vivo* into the lateral ventricle dramatically increases the number of neurospheres formed *in vitro*. Animals were treated with 33  $\mu\text{g/ml}$  EGF-filled infusion pumps for 6 days prior to sacrifice. Subsequent culturing of the lateral ventricle walls in the presence of 20 ng/ml EGF resulted in a 4-fold increase in the number of neurospheres formed after 9 days *in vitro* as compared to control animals that received infusions of saline for the same 6 days.

**Figures 6a and 6b** depict the time it takes to reconstitute the number of proliferating cells in the subependyma after a single series of 3H-thymidine injections (Fig. 6a) and after a second series of 3H-thymidine injections given 2 days after the first series (Fig. 6b). As shown in Figure 6a, one day after a single series of injections only 10% of the subependymal cells were proliferating relative to control values (no 3H-thymidine injection). There was a continual increase in the number of proliferating cells over time and by 8 days, the number of proliferating subependymal cells had returned to control values. When a second series of injections was given two days after the first series, as shown in Figure 6b (open circles) the number of stem cells was depleted and the proliferating population was reduced to 50% of control values. When the second series of injections was given four days after the first series (open squares) the number



of stem cells which were recruited to repopulate the subependyma had exited from the cell cycle and were no longer proliferating. Hence, they were not killed by the second series of injections on day 4. In this case, the number of proliferating subependymal cells returned to 85% of the control values 8 days after the second series of injections.

#### Detailed Description of the Invention

##### ***Definitions***

The term "stem cell" refers to a relatively quiescent undifferentiated cell which is capable of proliferation and giving rise to more stem cells having the ability to generate a large number of progenitor cells that can in turn give rise to differentiated, or differentiable daughter cells.

The term "neural stem cell" refers to multipotent stem cells capable of differentiation into neurons and glia.

The term "progenitor cell" refers to an undifferentiated cell derived from a CNS stem cell. The progenitor cell has limited proliferative ability and cannot self-renewal. It is committed to a particular path of differentiation and will, under appropriate conditions, eventually differentiate into glia or neurons.

The term "oligodendrocyte" refers to a differentiated glial cell which forms the myelin surrounding axons in the central nervous system (CNS). Oligodendrocytes are of the phenotype galactocerebroside (+), myelin basic protein (+), and glial fibrillary acidic protein (-) [GalC(+), MBP(+), GFAP(-)].

The term "neuron" refers to a differentiated neuronal cell having the phenotype neuron specific enolase (+), neurofilament (+), microtubule associated protein (+), or Tau-1 (+) [NSE(+), NF (+), MAP-2 (+), or Tau-1 (+)].

The term "astrocyte" refers to a differentiated glial cell that is GFAP(+), GalC(-), and MBP(-).

The term "neurosphere" refers to a cluster of cells derived from neural stem cells and cultured *in vitro*. At least some of the cells are of the nestin (+) phenotype. The cluster is comprised of stem cells and/or progenitor cells and may or may not include differentiated cells.

- 5 The term "precursor cells" refers to the living cells modified or manipulated by the methods of the instant invention that are derived from neural stem cells, *in vivo* or *in vitro*, and includes both progenitor and stem cells. *In vitro*, precursor cells typically grow in the form of neurospheres, but may exhibit different growth patterns depending upon culture conditions. Precursor cells are found in the subependyma but are not  
10 limited to this CNS region.

The term "growth factor" refers to a protein, peptide or other molecule having a growth, proliferative, differentiative, or trophic effect on precursor cells.

- The term "neurological agent" refers to any biologically active substance useful for the functioning of CNS cells. For example, the term encompasses neurotransmitters,  
15 neurotransmitter receptors, growth factors, growth factor receptors, and the like, as well as enzymes used in the synthesis of these agents.

- The term "ventricle" refers to any cavity or passageway within the central nervous system through which cerebral spinal fluid flows. Thus, the term not only encompasses the lateral, third, and fourth ventricles, but also encompasses the central  
20 canal and the cerebral aqueduct.

The term "ventricular tissue" refers to the tissue lining CNS ventricles and includes the subependyma which comprises a collection of undifferentiated cells including CNS stem cells and progenitor cells.

- The term "constitutively proliferating population" refers to the population of dividing  
25 cells located within the subependyma of the lateral ventricles of the adult mammalian forebrain [as outlined by Smart (J. Comp. Neurol., 116:325, 1961)], and makes up

approximately 33% of the cells in some regions of the subependyma (Morshead and van der Kooy J. Neurosci., 12:249, 1992).

The term "genetic material" refers to the RNA and DNA that encodes a neurological agent selected from the group consisting of growth factors, growth factor receptors, 5 neurotransmitters, neurotransmitter receptors, neuropeptides, growth factor synthesizing enzymes, and neurotransmitter synthesizing enzymes. The genetic material is used to infect precursor cells *in vitro* or *in vivo* using genetic modification techniques known in the art.

#### Description of the Preferred Embodiments

##### 10 ***In Vitro Isolation and Characterization of Stem Cells From the Adult Mammalian CNS***

CNS stem cells have been reported and their potential use described (Reynolds and Weiss, Science 255:1707 [1992]; Reynolds et al., J. Neurosci. 12:4565 [1992]; Reynolds and Weiss, Restorative Neurology and Neuroscience 4:208 [1992]; Reynolds 15 and Weiss, Neuronal Cell Death and Repair, ed Cuello [1993]). Additionally, the utility of these cells is described in copending applications U.S.S.N. 07/726,812; 07/961,813; 07/967,622; and 08/010,829. Like stem cells found in other mammalian tissues, the CNS stem cell is capable of self maintenance and generating a large number of progeny -- these include neurons, astrocytes and oligodendrocytes.

20 CNS precursor cells can be isolated and cultured from the adult mammalian CNS by the methods (described in Example 2 below) of Reynolds and Weiss (Science 255:1707, 1992), and co-pending applications referenced above. In brief, the epidermal growth factor (EGF)-responsive stem cell, is grown in a defined serum-free medium in the presence of at least one growth factor. Growth factors which may be 25 used for inducing proliferation include any trophic factor which allows precursor cells to proliferate, including any molecule which binds to a receptor on the surface of the cell to exert a trophic, or growth-inducing effect on the cell. Such factors include nerve growth factor (NGF), acidic and basic fibroblast growth factors (aFGF, bFGF), platelet-derived growth factor (PDGF), thyrotropin releasing hormone (TRH), 30 epidermal growth factor (EGF), an EGF-like ligand, amphiregulin, transforming

- growth factor alpha and beta ( $TGF\alpha$ ,  $TGF\beta$ ), insulin-like growth factor ( $IGF_{1}$ ) and the like. The cell is induced to divide giving rise to a cluster of undifferentiated cells. The clusters of cells are not immunoreactive for GFAP, neurofilament (NF), neuron-specific enolase (NSE) or MBP. However, precursor cells within the cluster are
- 5 immunoreactive for nestin, an intermediate filament protein found in undifferentiated CNS cells. The nestin marker was characterized by Lehn Dahl et al., Cell 60:585-595 (1990). The mature phenotypes associated with the four cell types which may be differentiated from the progeny of the precursor cells are predominantly negative for the nestin phenotype.
- 10 In the continued presence of a mitogen such as EGF or the like, precursor cells within the neurosphere continue to divide resulting in an increase in the size of the neurosphere and the number of undifferentiated cells [nestin(+), GFAP(-), NF(-), NSE (-), MBP (-)]. At this stage, the cells are non-adherent and tend to form the free-floating clusters characteristic of neurospheres. However, culture conditions may
- 15 be varied so that while the precursor cells still express the nestin phenotype, they do not form the characteristic neurospheres. After removal of the mitogen, the cells adhere to the substrate (poly-ornithine-treated plastic or glass), flatten, and begin to differentiate into neurons and glial cells. At this stage the culture medium may contain serum such as 0.5-1.0% fetal bovine serum (FBS). Within 2-3 days, most or
- 20 all of the precursor cells begin to lose immunoreactivity for nestin and begin to express antigens specific for neurons, astrocytes or oligodendrocytes as indicated by immunoreactivity for MAP-2, GFAP and GalC, respectively.

The identification of neurons is also accomplished using immunoreactivity for neuron-specific enolase (NSE), neurofilament, and the neuron specific protein tau-1. Because

25 these markers are highly reliable, they will continue to be useful for the primary identification of neurons, however neurons can also be identified based on their specific neurotransmitter phenotype.

Using dual-label immunofluorescence and immunoperoxidase methods, differentiated neurosphere cultures can be analyzed for the expression of neurotransmitters, or in

30 some cases for the enzymes responsible for the neurotransmitter synthesis.

Alternatively, in situ hybridization histochemistry can be performed using cDNA or RNA probes specific for the peptide neurotransmitter or the neurotransmitter synthesizing enzyme mRNAs. These techniques can be combined with immunocytochemical methods to enhance the identification of specific phenotypes.

- 5 If necessary, the antibodies and molecular probes discussed above can be applied to western and northern blot procedures respectively to aid in the cell identification.

Cells that do not express intermediate filaments specific for neurons or for astrocytes, begin to express markers specific for oligodendrocytes in a correct temporal fashion. That is, the cells first become immunoreactive for O4 (a cell surface antigen),  
10 galactocerebroside (GalC, a myelin glycolipid) and finally, myelin basic protein (MBP). These cells also possess a characteristic oligodendrocyte morphology.

CNS stem cells have been isolated from a variety of adult CNS regions, including the conus medullaris (see Fig. 1a-1c), thoracic spinal cord, brain stem, and hypothalamus. In each of these cases the isolated CNS stem cell exhibits self-maintenance and  
15 generates a large number of progeny which include neurons, astrocytes and oligodendrocytes. Thus stem cells are present in multiple regions of the adult mammalian CNS.

#### ***Characterization and Manipulation of Stem Cells from the Adult Mammalian CNS In Vivo***

- 20 The techniques that are described above to isolate, proliferate, and differentiate, CNS stem cells *in vitro* can be adapted to *in vivo* techniques, as described below, to achieve similar results. Such *in vivo* manipulation and modification of these cells allows cells lost, due to injury or disease, to be endogenously replaced, thus obviating the need for transplanting foreign cells into a patient. Additionally, the cells can be modified  
25 or genetically engineered *in vivo* so that they express various biological agents useful in the treatment of neurological disorders.

Normally, the adult mammalian CNS is mitotically quiescent *in vivo* with the exception of the subependymal region lining the lateral ventricles in the forebrain. This region contains a subpopulation of constitutively proliferating cells with a cell

cycle time of 12.7 hours. BrdU and retroviral labelling of the proliferating cells reveal that none of the newly generated cells differentiate into mature neurons or glia nor do they migrate into other CNS regions (Morshead and Van der Kooy, supra).

5 The continual proliferation and maintenance of a constant number of cells within the subependyma is explained by two mechanisms. The death of one of the daughter cells after each division maintains the proliferating population at a constant number. The constitutively dividing population eventually dies out and a subpopulation of relatively quiescent cells within the subependyma is able to repopulate the constitutively dividing population. This stem cell-like mode of maintaining the proliferative subependymal  
10 population is analogous to other tissues where cells have a short life span and are repopulated by a subpopulation of relatively quiescent cells referred to as stem cells.

As detailed in Example 1, experiments utilizing retrovirus infection of these proliferating cells *in vivo* and subsequent  $\beta$ -galactosidase ( $\beta$ -gal) reporter gene expression as a non-diluting marker show that with increasing adult mice survival  
15 times (of up to 28 days post retrovirus infection) there is a progressive loss of  $\beta$ -gal positive subependymal cells. Relative to 1 day survival animals, 6 days following retrovirus injection there is a 45% loss of  $\beta$ -gal positive cells and 28 days following retrovirus infection there is a 97% loss. Using nested PCR to identify single cells containing retroviral DNA it was determined that the loss of  $\beta$ -gal expressing cells is  
20 due to the loss of the retrovirally infected cells through cell death, not due to the turn-off of  $\beta$ -gal expression.

Intraperitoneal injections of BrdU (a thymidine analog that is incorporated into the DNA of dividing cells) reveal that 33% of the cells within some regions of the subependyma make up the normally dividing population (see Example 9 below). The  
25 number of BrdU labelled cells decreases over time. By 30 days after BrdU labelling, only 3% of the dividing cells are still labelled. The heavy labelling of a small number of cells 30 days after BrdU injections demonstrates that the labelled cells were dividing at the time of the injections and suggests that they were relatively quiescent

for the 30 day period. This indicates that these cells are stem cells rather than cells of the constitutively proliferating population.

The above two examples support the hypothesis that the maintenance of the constant number of proliferating subependymal cells seen throughout adult life requires the presence of a relatively quiescent stem cell that proliferates sporadically to replenish the constitutively proliferating population and to self-renew.

As detailed in Example 5, the constitutively dividing subependymal cells can be killed off by injecting high doses of radioactive thymidine for the duration of the cell cycle at intervals less than S-phase duration. At one day post-kill the proliferating population is 10% of controls and by 8 days the proliferating population is back to control levels. If the replenished population is due to the recruitment of normally quiescent cells into the proliferative mode, then a second kill at the time that stem cells are generating progeny to repopulate the subependyma should alter the number of cells within the constitutively proliferating population. When a second kill is done 2 days after the initial kill, 8 days later the constitutively proliferating population is only 45% of the control values (animals receiving no thymidine kill treatment) or animals that received only one kill at day 0 (the time of the first kill) (see Fig. 6b). The reduction in the number of proliferative cells in the subependyma is maintained at 63% even at 31 days after the second kill. When a second kill is done on day 4, the proliferating population returns to 85% of control values 8 days later. These results suggest that the normally quiescent stem cell is recruited into the proliferative mode within the first two days after the initial kill and that by 4 days the stem cell no longer needs to be recruited to repopulate the subependyma (see Fig. 2).

As detailed in Example 6 below, an experiment was performed to determine whether the *in vitro* stem cell is derived from the constitutively proliferating population or from the quiescent population. Animals were treated in one of the following ways:

Group 1. Control

High doses of radioactive thymidine were given on:

Group 2. day 0

Group 3. day 0 and day 2

Group 4. day 0 and day 4

Following the last injection animals were killed and stem cells isolated from the striatum (including the subependymal region) via the methods described in Example 2 below.

- 5 In groups 2-4 the constitutively proliferating population was killed. In group 3 stem cells that are recruited into the cell cycle to repopulate the subependymal proliferating cells were also killed.

Number of Neurospheres produced *in vitro*:

	Group 1.	100% (Control)
10	Group 2.	100%
	Group 3.	45%
	Group 4.	85%

These results demonstrate that when you eliminate nearly all of the constitutively proliferating cells in the subependyma this does not affect the number of stem cells that can be isolated and proliferated *in vitro* (group 1 vs. group 2 and 4). However, when the normally quiescent cells are killed when they are recruited to repopulate the subependyma (as with group 3) the number of stem cells that can be isolated *in vitro* is significantly reduced (group 3 vs. group 1 and 2). By 4 days after the first kill most of the stem cells themselves are no longer turning over and as a result are not killed by the second series of tritiated thymidine injections (hence, only a 15% reduction [group 4] compared to 55% reduction [group 3]).

The above results demonstrate that *in vitro* stem cells are derived from the quiescent population of subependymal cells *in vivo* (see Fig. 3). This also explains why stem cells can be derived from CNS ventricular regions, other than the forebrain, which do not have the subpopulation of constitutively proliferating cells. Thus, having determined the relationship between the constitutively proliferating population of subependymal cells and the relatively quiescent stem cells of the lateral ventricles, one can take advantage of the characteristics of these cell populations to more effectively manipulate them *in vivo*. Such techniques allow the use and manipulation of



endogenous cells for the treatment of a variety of neurological disorders. It has been found that the same factors that influence proliferation and differentiation of the cells *in vitro* also achieve the same effects *in vivo*. Thus, for example, cells can be manipulated *in situ* by the administration of growth factors and combinations of growth factors that result in specified outcomes. For example, the *in vitro* differentiation methods disclosed in copending application U.S.S.N. 07/967,622 in which cells can be induced to follow a particular differentiative pathway, can be modified using the methods described herein to achieve similar results *in vivo*. The growth factors can be administered to a ventricle by stereotactic injection, implantation of an osmotic pump, or any other suitable method.

The quiescent neural stem cells are located throughout the CNS near ventricular regions. Within the forebrain are the lateral (first and second) ventricles. The third ventricle is a cavity of the lower part of the forebrain. The cavity of the midbrain is the tubular shaped cerebral aqueduct and connects the third ventricle with the cavity within the hindbrain, the fourth ventricle. The central canal is the passageway for cerebral spinal fluid within the spinal cord.

The fact that CNS stem cells are located in the tissues lining ventricles offers several advantages for the modification and manipulation of these cells *in situ* and the ultimate treatment of various neurological diseases, disorders, and injury that affect different regions of the CNS. Therapy for these can be tailored accordingly so that stem cells surrounding ventricles near the affected region would be manipulated or modified *in situ* using the methods described herein. The ventricular system is found in nearly all brain regions and thus allows easier access to the affected areas. If one wants to modify the stem cells by exposing them to a growth factor or a viral vector it is relatively easy to implant an osmotic pump or make injections into the ventricles. This would allow the migration of the CNS stem cell progeny into regions which have been damaged as a result of injury or disease. Furthermore, the close proximity of the ventricles to many brain regions would allow for the diffusion of a secreted neurological agent by the stem cells or their progeny. For treatment of Huntington's Disease, Alzheimer's Disease, Parkinson's Disease, and other neurological disorders affecting primarily the forebrain, growth factors or other neurological agents would

be delivered to the ventricles of the forebrain to affect *in situ* modification or manipulation of the stem cells. For the treatment of multiple sclerosis and other demyelinating or hypomyelinating disorders, and for the treatment of Amyotrophic Lateral Sclerosis or other motor neuron diseases, growth factors or other neurological agents would be delivered to the central canal. Other diseases and disorders which would be treated by the methods of the present invention are disclosed in copending application U.S.S.N 07/726,812.

In addition to treating CNS tissue immediately surrounding a ventricle, a viral vector, DNA, growth factor, or other neurological agent can be easily administered to the lumbar cistern for circulation throughout the CNS.

Under normal conditions subependymal precursors do not differentiate or migrate, rather, their fate appears to be cell death after an undefined number of cell divisions (Morshead and Van der Kooy, 1992). This explanation is also supported by PCR evidence, as described above. Injection of growth factors into the lateral ventricle alters this fate. As described in more detail in Example 1 below, retroviruses were injected into the lateral ventricles for six consecutive days. Implanting cannulae attached to EGF-filled osmotic pumps into the lateral ventricles on the same day as (and 1 or 6 days following) retrovirus injection results in an increase in the total number of RV- $\beta$ -gal labelled cells 6 days later (from an average of 20 cells/brain to 150 cells/brain).

It is known from the PCR experiments described above that 6 days following retroviral injection no cells exist that contain non-expressed retroviral DNA. Thus these results indicate that the EGF-induced increase in  $\beta$ -gal positive cell number is due to the expansion of the clone size of the retrovirally labelled constitutively proliferative population. It is also possible that part of this increase is due to the activation by EGF of a relatively quiescent stem cell.

Interestingly, this expansion of the number of  $\beta$ -gal labelled cells is accompanied by the migration of these cells away from the subependymal medially and laterally (and possibly rostrally and caudally) up to a distance of approximately 400  $\mu$ m (see Fig.

4), with subsequent differentiation. Thus, infusion of EGF or similar growth factors induces the proliferation, migration and differentiation of neural stem cells and progenitor cells *in vivo*, and can be used therapeutically to replace neural cells lost due to injury or disease. In a preferred embodiment EGF and FGF are administered  
5 together or sequentially.

The normal fate of the constitutively proliferating cell population (i.e. cell death) can be altered by administering Bcl-2 or genetically modifying the cells with the bcl-2 gene. The gene product is known to prevent programmed cell death (apoptosis) in a variety of cell types. Similar to the EGF experiments, a clonal expansion of the  
10 constitutively proliferating cell population is achieved.

The *in vivo* techniques described herein can be used to genetically modify CNS stem cells and progenitor cells. Any useful genetic modification of the cells is within the scope of the present invention. For example, the cells may be modified to produce or increase production of a neurological agent such as a neurotransmitter, growth  
15 factor, or the like. The genetic modification is performed either by infection of the cells lining CNS ventricular regions with recombinant retroviruses or transfection using methods known in the art (see Maniatis et al., in *Molecular Cloning: A Laboratory Manual*, Cold Spring Harbor Laboratory, N.Y. (1982)). Any method of genetic modification, now known or later developed can be used. With direct DNA  
20 transfection, cells could be modified by particle bombardment, receptor mediated delivery, and cationic liposomes. When chimeric gene constructs are used, they generally will contain viral, for example retroviral long terminal repeat (LTR), simian virus 40 (SV40), cytomegalovirus (CMV); or mammalian cell-specific promoters such as tyrosine hydroxylase (TH), dopamine  $\beta$ -hydroxylase (DBH), phenylethanolamine  
25 N-methyltransferase (PNMT), choline acetyltransferase (ChAT), glial fibrillary acidic protein (GFAP), neuron-specific enolase (NSE), the neurofilament (NF) proteins (NF-L, NF-M, NF-H, and the like) that direct the expression of the structural genes encoding the desired protein.

If a retroviral construct is to be used to genetically modify normally quiescent stem  
30 cells, then it is preferable to induce the proliferation of these cells using the methods

described herein. For example, an osmotic infusion pump could be delivered to the central canal several days prior to infection with the retrovirus. This assures that there will be actively dividing neural stem cells which are susceptible to infection with the retrovirus.

- 5 When the genetic modification is for the production of a biologically active substance, the substance will generally be one that is useful for the treatment of a given CNS disorder. For example, it may be desired to genetically modify cells so they secrete a certain growth factor product. Growth factor products useful in the treatment of CNS disorders include, but are not limited to, nerve growth factor (NGF), brain-  
10 derived neurotrophic factor (BDNF), the neurotrophins (NT-3, NT-4/NT-5), ciliary neurotrophic factor (CNTF) and other cytokines, amphiregulin, bFGF, aFGF, EGF, TGF $\alpha$ , TGF $\beta$ , PDGF, IGFs, and the interleukins.

- Cells can also be modified *in vivo* to express a certain growth factor receptor (r) including, but not limited to, p75 low affinity NGFr, CNTFr, the *trk* family of  
15 neurotrophin receptors (*trkA*, *trkB*, *trkC*), EGFr, FGFr, and amphiregulin receptors. Cells can be engineered to produce various neurotransmitters or their receptors such as serotonin, L-dopa, dopamine, norepinephrine, epinephrine, tachykinin, substance-P, endorphin, enkephalin, histamine, N-methyl D-aspartate (NMDA), glycine, glutamate,  $\gamma$ -amino butyric acid (GABA), acetylcholine, and the like. Useful neurotransmitter-  
20 synthesizing genes include TH, dopa decarboxylase (DDC), DBH, PNMT, glutamic acid decarboxylase (GAD), tryptophan hydroxylase, ChAT, and histidine decarboxylase. Genes that encode for various neuropeptides, which may prove useful in the treatment of CNS disorders, include substance-P, neuropeptide-Y (NP-Y), enkephalin, vasopressin, vasoactive intestinal peptide (VIP), glucagon, bombesin,  
25 cholecystokinin (CCK), somatostatin, calcitonin gene-related peptide (CGRP), and the like.

#### ***Improvement to In Vitro Techniques for Proliferation of CNS Stem Cells***

- The absolute yield of the number of precursor cells isolated *in vitro* from the mammalian CNS can be increased dramatically by injecting a growth factor or  
30 combination of growth factors, for example EGF, FGF, or EGF and FGF together,

into the ventricles *in situ* as described above. As detailed in Example 10 below, 6 days after infusion of EGF into the lateral ventricle of a mouse forebrain, the walls of the ventricle were removed and the stem cells harvested. Infusion of EGF into the lateral ventricle increased the efficiency of the yield of stem cells that proliferated to form neurospheres.

This technical improvement of *in vitro* technology for the proliferation of CNS stem cells should prove invaluable when stem cells are to be harvested for later transplant back into a patient, thereby making the initial surgery 1) less traumatic because less tissue would have to be removed and 2) more efficient because a greater yield of stem cells per surgery would proliferate *in vitro*. Additionally, the patient's stem cells, once they have proliferated *in vitro*, could also be genetically modified *in vitro* using the techniques described in copending application U.S.S.N. 08/010,829. The *in vitro* genetic modification may be more desirable in certain circumstances than *in situ* techniques when more control over the infection with the genetic material is required.

In order that the invention described herein may be more fully understood, the following examples are set forth. It should be understood that these examples are for illustrative purposes only and are not to be construed as limiting the scope of the invention in any manner.

### EXAMPLES

#### Example 1

A replication incompetent retrovirus containing the  $\beta$ -galactosidase gene (as described in Walsh and Cepko, Science 241:1342, 1988) was injected into the forebrain lateral ventricles of CD1 adult male mice (25-30 g from Charles River). The injected retrovirus was harvested from the BAG cell line (ATCC CRL-9560) according to the method of Walsh and Cepko (*supra*). Mice were anesthetized using 65 mg/kg, i.p. sodium pentobarbital. Unilateral stereotactic injections of 0.2-1.0  $\mu$ l of retrovirus were injected into the lateral ventricle using a 1  $\mu$ l Hamilton syringe. The coordinates for injection were AP +4.2 mm anterior to lambda, L  $\pm$  0.7 mm, and DV -2.3 mm below dura, with the mouth bar at -2mm below the interaural line.

- On the same day as, one day, or six days following the retrovirus injection, an infusion cannulae attached to a 0.5  $\mu$ l/hour ALZET osmotic mini-pumps filled with 3.3 - 330  $\mu$ g/ml of EGF were surgically implanted into the lateral ventricles at the identical stereotactic coordinates as stated above. The infusion cannula kits were
- 5 obtained from ALZA. The infusion cannulae were cut to 2.7 mm below the pedestal. The pumps were secured to the mouse skull by use of acrylic cement and a skull screw contralateral and caudal to the injection site. The osmotic mini-pump was situated subcutaneously under and behind the armpit of the left front paw and connected to the infusion cannula by the means of polyethylene tubing.
- 10 Six days following initiation of EGF infusion the animals were sacrificed with an overdose of sodium pentobarbital. Mice were transcardially perfused with 2% buffered paraformaldehyde, and the brains were excised and post fixed overnight with 20% sucrose in 2% buffered paraformaldehyde. Coronal slices were prepared with - 20 celsius cryostat sectioning at 30  $\mu$ m. Slices were developed for  $\beta$ -gal
- 15 histochemistry as per Morshead and Van der Kooy (*supra*).

Under these conditions, regardless of the day post retrovirus injection, infusion of EGF resulted in an expansion of the population of  $\beta$ -gal labelled cells from an average of 20 cells per brain up to an average of 150 cells per brain and the migration of these cells away from the lining of the lateral ventricles (see Fig. 4). Infusion of basic

20 fibroblast growth factor (bFGF), 33  $\mu$ g/ml resulted in an increase in the number of  $\beta$ -gal labelled cells, but this increase was not accompanied by any additional migration. Infusion of EGF and FGF together resulted in an even greater expansion of the population of  $\beta$ -gal labelled cells from 20 cells per brain to an average of 350 cells per brain.

- 25 These results indicate that FGF may be a survival factor for relatively quiescent stem cells in the subependyma layer, whereas EGF may act as a survival factor for the normally dying progeny of the constitutively proliferating population. The synergistic increase in  $\beta$ -galactosidase cell number when EGF and FGF are infused together further reflects the direct association between the relatively quiescent stem cell and the
- 30 constitutively proliferating progenitor cell.

### Example 2

The striata, including the subependymal region, of female, pathogen-free CD1 albino mice [3 to 18 month old; Charles River (CF1 and CF2 strains yielded identical results)] were dissected and hand cut with scissors into 1-mm coronal sections and  
5 transferred into artificial cerebrospinal fluid (aCSF) containing 124 mM NaCl, 5 mM KCl, 1.3 mM  $MgCl_2$ , 2 mM  $CaCl_2$ , 26 mM  $NaHCO_3$ , and 10 mM D-glucose (pH 7.35, approx. 180 mOsmol), aerated with 95%  $O_2$  - 5%  $CO_2$  at room temperature. After 15 minutes the tissue sections were transferred to a spinner flask (Bellco Glass) with a magnetic stirrer filled with low- $Ca^{2+}$  aCSF containing 124 mM NaCl, 5 mM  
10 KCl, 3.2 mM  $MgCl_2$ , 0.1 mM  $CaCl_2$ , 26 mM  $NaHCO_3$ , and 10 mM D-glucose (pH 7.35, approx. 180 mOsmol), aerated with 95%  $O_2$  - 5%  $CO_2$  at 32 to 35° C., containing 1.33 mg/ml of trypsin (9000 BAEE units/mg), 0.67 mg/ml of hyaluronidase (2000 units/mg) and 0.2 mg/ml of kynurenic acid. After 90 minutes, tissue sections were transferred to normal aCSF for 5 minutes prior to trituration.  
15 Tissue was transferred to DMEM/F-12 (A:1, Gibco) medium containing 0.7 mg/ml ovomucoid (Sigma) and triturated mechanically with a fire-narrowed pasteur pipet. Cells were plated (1000 viable cells per plate) in noncoated 35 mm culture dishes (Costar) containing serum-free medium [this included a defined hormone mix and salt mixture that included insulin (25  $\mu g/ml$ ), transferrin (100  $\mu g/ml$ ), progesterone (20  
20 nM), putrescine (60  $\mu M$ ), and selenium chloride (30 nM); glucose (0.6%); glutamine (2 mM); sodium bicarbonate (3 mM); and HEPES buffer (5 mM)] and EGF [20 ng/ml, purified from mouse sub-maxillary gland (Collaborative Research)] or human recombinant (Gibco/BRL). Cells were allowed to settle for 3-10 minutes after which the medium was aspirated away and fresh DMEM/F-12/hormone mix/EGF was added.  
25 After 5-10 days *in vitro* the number of spheres (neurospheres) were counted in each 35 mm dish.

### Example 3.

A retroviral construct containing the human bcl-2 gene and the  $\beta$ -galactosidase gene is microinjected into the adult mouse lateral ventricle. A control mouse is injected  
30 with a retroviral construct containing only the  $\beta$ -galactosidase gene. One of the two progeny of each of the constitutively proliferating subependymal cells of the adult lateral ventricle normally dies within a few hours after division. The bcl-2 gene

product prevents the programmed death of cells in several other tissues. In the adult subependyma, single cells infected with both the  $\beta$ -galactosidase and bcl-2 genes are marked by expression of both these gene products. These cells are identified in brain tissue slices with antibodies specific to  $\beta$ -galactosidase and human Bcl-2. Proliferating  
5 infected subependymal cells so infected produce larger numbers of cells per clone relative to the control. Thus, Bcl-2 induces the survival of the one normally dying progeny of each division of a constitutively proliferating adult subependymal cell. Moreover, the bcl-2 infected progeny migrate out into striatal and septal tissue to produce new neurons and glia. This indicates that EGF and Bcl-2 act as a survival  
10 factors for the normally dying progeny of constitutively proliferating adult subependymal cells which generate new neurons and glia *in vivo*.

#### Example 4.

A retroviral construct containing the nerve growth factor gene is microinjected (as was the construct in Example 1) to infect the constitutively proliferating adult  
15 subependymal cells of the lateral ventricle. Thus, these cells are used to produce an endogenous growth factor in the adult brain. Levels of nerve growth factor produced by the transfected cells are measured directly by radioimmunoassay and (from a direct functional assay) by rescue of basal forebrain cholinergic neurons *in vivo* after axotomy injury in the model developed by Gage and collaborators (P.N.A.S. 83:9231,  
20 1986).

#### Example 5.

Adult male CD1 mice received a series of intraperitoneal injections of 3H-thymidine (0.8 ml per injection, specific activity 45-55 mCi/mole, ICN Biomedical) on day 0 (3 injections, 1 every 4 hours) in order to kill the constitutively proliferating  
25 subependymal cells. On day 0.5, 1, 2, 4, 6, 8 or 12, animals received 2 BrdU injections 1 hour apart (see Example 9) and were sacrificed 0.5 hour after the last injection.

It was observed that 10% of the cells were proliferating on day 1 post-kill, and by 8 days the number of proliferating cells had reached 85% (see Fig. 6a), which was not



statistically significantly different from control values. Animals were sacrificed and the brains were removed and processed as described in Example 9.

In a second group of animals, 3H-thymidine injections were given on day 0 (3 injections, 1 every 4 hours), followed by an identical series of injections on day 2 or  
5 4. Animals were allowed to survive for 8 days following the second series of injections (days 9, 10 and 12 respectively) at which time they received 2 injections of BrdU and were sacrificed 0.5 hours later. Animals were sacrificed and the brains were removed and processed as described in Example 9.

After the second series of injections on day 2 only 45% of the proliferating population  
10 had returned relative to control values. This indicates that the second series of injections given on day 2 had killed the stem cells as they were recruited to the proliferating mode (see Fig. 6b). The second series of injections given on day 4 resulted in a return to control values by day 8 suggesting that by this time, the stem cells were no longer proliferating and hence were not killed by the day 4 series of  
15 injections (Fig. 6b).

#### Example 6.

Adult male CD1 mice were divided into 4 groups. Group A animals received a series of 3H-thymidine injections on day 0 (3 injections, 1 every 4 hours). Animals in groups B and C received a series of 3H-thymidine injections on day 0 followed by a  
20 second series of injections on day 2 or 4. Group D animals received injections of physiological saline instead of 3H-thymidine over the same time course as group A. Animals from all groups were sacrificed by cervical dislocation 16-20 hours following the last series of injections. Brains were removed and the subependyma surrounding the lateral ventricles in the forebrain were dissected and cultured as described in  
25 Example 2 in order to assess the number of spheres that formed following each of the injection paradigms. The cells from each brain were plated into two 35 mm wells. At 6 and 8 days *in vitro*, the total number of spheres was counted in each of the 35 mm wells (see Fig. 3).

Control animals that received a series of saline injections formed the same number of spheres as animals that received 3H-thymidine on day 0 (which kills the normally proliferating subependymal cells). This indicates that the constitutively proliferating subependymal cells are not the source of stem cells isolated *in vitro*. Animals that  
5 received a second series of injections on day 2 formed 45% the number of spheres (similar to the number of proliferating subependymal cells observed *in vivo*). When a second series of injections was done on day 4, the number of spheres formed *in vitro* was not significantly different from control values, again correlating with the *in vivo* findings. Taken together, this data indicates that the multipotent spheres, which  
10 are isolated *in vitro* in the presence of EGF, are formed from the relatively quiescent stem cell population within the subependyma *in vivo*.

Example 7.

A retroviral construct containing the  $\beta$ -galactosidase gene is microinjected (as in Example 1) into the III ventricle of the diencephalon, IV ventricle of the brain stem  
15 and central canal of the spinal cord. Minipumps containing EGF and FGF are then used to continuously administer growth factors for six days (as in Example 1) into the same portion of the ventricular system that the retroviral construct was administered. This produces an increase in the number of  $\beta$ -galactosidase producing cells which survive and migrate out into the tissue near the III ventricle, IV ventricle and central  
20 canal of the spinal cord forming new neurons and glia.

Example 8.

A retroviral construct containing the tyrosine hydroxylase (TH) gene as well as the  $\beta$ -galactosidase gene is microinjected into the adult lateral ventricle as in Example 1. Minipumps containing EGF, FGF, or EGF and FGF together are then used to  
25 continuously administer the growth factor(s) into the lateral ventricle for 6 days as in Example 1. As the infected subependymal cells migrate out into the striatum they differentiate into neuronal cells that produce dopamine as measured directly by immunofluorescence with an antibody and (from a direct functional assay) by the ability to overcome the rotational bias produced by unilateral 6-hydroxydopamine  
30 lesions.

Example 9.

Adult male CD1 mice (25-30 g, Charles River) were injected intraperitoneally (i.p.) with bromodeoxyuridine (BrdU, Sigma, 65 mg/kg) every 2 hours for a total of 5 injections in order to label all of the constitutively proliferating cells in the subependyma lining the lateral ventricles in the forebrain. One month later, animals were sacrificed with an overdose of sodium pentobarbital and transcardially perfused using 4% paraformaldehyde. The brains were removed and post-fixed overnight in 4% paraformaldehyde with 20% sucrose. Brain sections were cut on a cryostat (30 um) and collected in washing buffer (0.1 M PBS pH 7.2 with 1% normal horse serum and 0.3% Triton X-100). Sections were incubated in 1M HCl at 60° C. for 0.5 hours then washed 3 times (10 minutes each) in washing buffer. Following the final wash, sections were incubated in anti-BrdU (Becton Dickinson, 1:25) for 45 hours at 4° C. After incubation in the primary antibody, sections were washed 3 times and incubated for 1 hours in biotinylated horse-anti-mouse secondary antibody (Dimension Lab, 1:50) at room temperature followed by another 3 washes. The sections were then incubated for 1 hour in avidin conjugated FITC (Dimension Lab, 1:50) at room temperature and washed a final 3 times. Sections were mounted on gelatin coated slides, air-dried and coverslipped with Fluoromount. Slides were examined for BrdU positive cells using a NIKON fluorescent microscope. The number of BrdU positive cells was counted within the subependyma surrounding the lateral ventricles in 8 samples in sections between the closing of the corpus callosum rostrally and the crossing of the anterior commissure caudally. It was found that 31 days following the series of BrdU injections, 3% of the subependymal cells were still labeled compared to control animals sacrificed immediately following the series of injections (control 100%).

Example 10

EGF pumps were implanted as described in Example 1. Animals were sacrificed by cervical dislocation 6 days after the pump was implanted. Brains were removed and stem cells isolated and counted as described in Example 2.

As shown in Figure 5, animals infused with EGF into the lateral ventricles for 6 days prior to sacrifice and brain culturing had 4 times as many spheres forming after 9 days

*in vitro* compared to control animals which received saline pumps for the same 6 day period. Thus, infusing EGF into the lateral ventricles *in vivo* prior to removal of precursor cells greatly increases the yield of stem cells which proliferate and form neurospheres *in vitro*.

5 Example 11.

Infusion of EGF (and/or FGF) into the lateral ventricles (see Example 1) results in the proliferation of the precursor cells *in situ* and may result in the differentiation and migration of de novo generated nerve cells (neurons, astrocytes, oligodendrocytes, see Fig. 4). Lesion studies and infusion of EGF into CNS neurodegeneration or  
10 dysfunction models results in the generation of new neurons replacing those lost to injury or disease, thereby imparting a gain in CNS function to these patients.

Example 12.

EGF and FGF is infused into the lateral ventricles (see Example 1) (or other CNS ventricular regions that contain quiescent stem cells). The CNS stem cells are then  
15 isolated and proliferated *in vitro* using proliferation methods such as that described in Example 2. This procedure results in an increase in the number of stem cells that are generated and an increase in the number of neurospheres (see Fig. 5). Neurospheres generated by this method are used as a source of donor cells for later transplantation into degenerated areas of human adult CNS. Neurospheres can also be proliferated  
20 accordingly from a patient's own CNS stem cells and transplanted back into the patient.

All references cited herein are hereby incorporated by reference.